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KINETICS AND MATHEMATICAL MODELING OF THE DRYING PROCESS OF MACAÚBA ALMONDS[1]

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ABSTRACT - The study of drying kinetics is fundamental for making the correct choice of time and temperature to be used in the drying process. In addition, mathematical modeling enables the simulation, optimization, sizing, and determination of the commercial application of the drying system. Therefore, the objective of this study was to investigate the kinetics and mathematical modeling of the drying process of macaúba almond [*Acrocomia aculeata* (Jacq.) Lodd. ex Mart] performed at different temperatures. For this purpose, the drying was performed under three different temperatures: 40 °C, 50 °C, and 60 °C. Four repetitions were performed for each temperature. The experimental data were fitted by nine different mathematical models. The choice of the best model was based on the following statistical parameters: magnitude of the adjusted coefficient of determination, magnitude of the mean relative error, and standard error of the estimate. It was observed that an increase in the drying temperature resulted in a reduction of drying time. The shortest drying time was observed in the treatment performed under 60 °C in which the almonds attained equilibrium moisture content at 34.08 h. The longest drying time was observed in the treatment performed under 40 °C, with the almonds attaining equilibrium moisture content at 404.40 h. Approximation of Diffusion, Midilli, Page, and Modified Page were the models that best described the drying process of macaúba almonds with the aim of subsidizing the design of industrial dryers.

Keywords: *Acrocomia aculeate*. Mathematical models. Simulation. Dehydration.

CINÉTICA E MODELAGEM MATEMÁTICA DO PROCESSO DE SECAGEM DE AMÊNDOAS DE MACAÚBA

RESUMO - O estudo da cinética de secagem é fundamental para a correta escolha do tempo e da temperatura utilizadas no processo. Além disso, a modelagem matemática possibilita a simulação, a otimização, o dimensionamento e a determinação da aplicação comercial do sistema de secagem. Diante do exposto, objetivou-se investigar a cinética e a modelagem matemática da secagem de amêndoas de macaúba [*Acrocomia aculeata* (Jacq.) Lodd. ex Mart] em diferentes temperaturas. A secagem foi realizada em três temperaturas: 40 °C, 50 °C, e 60 °C. Foram utilizadas quatro repetições para cada temperatura. Os dados experimentais se ajustaram em nove diferentes modelos matemáticos. A escolha do melhor modelo baseou-se nos seguintes parâmetros estatísticos: magnitude do coeficiente de determinação ajustado, magnitude do erro médio relativo e erro padrão da estimativa. O incremento da temperatura de secagem resultou na redução no tempo de secagem. O menor tempo de secagem foi observado no tratamento com temperatura de 60 °C, onde as amêndoas desse tratamento atingiram o teor de água de equilíbrio em 34,08 h. Já o maior tempo de secagem foi observado no tratamento 40 °C, com as amêndoas atingindo a umidade de equilíbrio em 404,40 h. Os modelos de Aproximação de Difusão, Midilli, Page e Page Modificado foram os mais adequados para descrever o fenômeno de secagem de amêndoas de macaúba, e subsidiar o dimensionamento de secadores industriais.

Palavras-chave: *Acrocomia aculeata*. Modelos matemáticos. Simulação. Desidratação.

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INTRODUCTION

Macaúba [*Acrocomia aculeata* (Jacq.) Lodd. ex Mart] is a palm tree found in abundance in tropical countries such as Brazil (SOUZA et al., 2016). This palm tree has many uses and aroused socioeconomic interest due to its potential of vegetable oil production and conversion into biofuels, foods, and cosmetics (COIMBRA; JORGE, 2011; BARRETO et al., 2016; EVARISTO et al., 2016a).

This palm tree can generate about 5 t/ha/year of oil (NAVARRO-DÍAZ et al., 2014), and this value is close to the productivity of oil palm (*Elaeis Guineenses*) (EVARISTO et al., 2016b). Its fruit consists of fibrous peel (epicarp), oleaginous pulp (mesocarp), a nut that has a very stony endocarp, and an oil-rich almond/seed.

The oil extracted from macaúba almonds has a high content of saturated fatty acids with a predominance of lauric acid. The stability of lauric acid and its creamy consistency make macaúba almond oil a valuable product for the cosmetic industry (MOTA et al., 2011). In addition, the endocarp, due to its characteristics, is a good raw material to produce resources such as charcoal and activated carbon (DUARTE et al., 2017).

Macaúba harvesting usually occurs during 4 months in a year. This can be a major obstacle to the industry as fruit processing had to be completed in a short period of time each year. In addition, the fruits have high moisture content after harvesting. This creates favorable conditions for the growth and development of microorganisms during storage (SILVA et al., 2019; SILVA et al., 2020). Thus, it is necessary to conduct research aimed at maintaining the quality of the endocarp oil. An efficient strategy for this purpose is drying.

Drying is the main conservation method used for agricultural products worldwide (KUMAR; KARIM; JOARDDER, 2014; SAMADI et al., 2014). Drying kinetics and mathematical modeling enable the simulation and optimization of the process as well as the sizing and determination of the commercial application of the drying system (PEREA-FLORES et al., 2012; BAPTESTINI et al., 2015). According to Silva et al. (2017), mathematical simulation and knowledge of the physiology, chemistry, and physical variations of agricultural products are useful for the development, evaluation, and optimization of dryers. In addition, mathematical models are used to design or improve new drying systems (GUIMARÃES FILHO et al., 2020). Several models are presented in the literature for the fitting the experimental data obtained from drying kinetics (SOUSA et al., 2017; SOUZA et al., 2019; LIMA et al., 2021).

However, to our knowledge, there is no information regarding the drying kinetics and mathematical modeling of the endocarp (almond) of macaúba fruits exposed to different temperatures, which makes it impossible to design dryers. Therefore, the aim of this study was to evaluate the drying kinetics and modeling of the drying process of macaúba almonds at different temperatures.

MATERIALS AND METHODS

The study was conducted at the Laboratory of Physical Properties and Quality of Agricultural Products of the National Center for Training in Storage (Centreinar), at the Federal University of Viçosa (UFV), Viçosa, Minas Gerais.

The macaúba fruits used in the experiment were manually harvested at the physiological maturation stage. The harvest was performed at the Capela farm in the municipality of Acaiáca, Minas Gerais, Brazil located at 20.76°S, 42.86°W and a 481 -m altitude above sea level in a humid subtropical climate (Cwa). The study sample consisted of approximately four adult plants. The palm trees were previously identified and georeferenced, and the ripe bunches were collected during the production period when the fruits were naturally detaching from the bunches. During the collection, a mattress with side nets was used to cushion the fall of the bunch and minimize mechanical damage.

After harvesting, the fruits were separated and selected while still in the field to eliminate those with damage, visible deformation, and disease and obtain a homogeneous product for the experimental units. After selection, they were transported to the laboratory of Physical Properties and Quality of Agricultural Products.

The fruits were stored in the laboratory for 20 days at a temperature of 30 °C ± 2 °C and relative humidity of 70% ± 5% (resting period). Drying was performed after the resting period. Storage allows the accumulation of oil in the mesocarp, considering that the fruit is climacteric.

After the 20 day period, the fruits' pulps were removed using a pulper, and the endocarp was subsequently cracked using a bench vise. Then, the almonds were subjected to the drying process. This step was performed in an air conditioning unit (model Aminco-Aire 150/300 CFM, Aminco) equipped with devices to control the temperature and relative humidity of the supplied air. The air flow was kept constant at around 4 $m^3/min/m^2$. Removable trays with screened bottoms were placed inside the equipment to allow air to pass through the sample. The drying of the macaúba fruit almonds was performed under three drying conditions 40 °C and 40.26%, 50 °C and 24.07%, and 60 °C and 14.91% of temperature and relative humidity, respectively. The samples were weighed periodically until the mass variation between three consecutive weighing was ≤0.01 g and equilibrium moisture content was thus attained. The experimental data obtained in the drying of macaúba almonds were used in regression models (Equations 1 to 9) that are frequently used to describe the drying process (Table 1).

Table 1. Mathematical models used for modeling the drying process of macaúba almonds.

Model name	Model	
Approximation of diffusion	$RU = a\ \exp(-kt) + (1 - a)\ \exp(-ktb)$	(1)
Henderson and Pabis	$RU = a\ \exp(-kt)$	(2)
Logarithmic	$RU = a\ \exp(-kt) + c$	(3)
Midilli	$RU = a\ \exp(-kt^n) + bt$	(4)
Modified Midilli	$RU = \exp(-kt^n) + bt$	(5)
Newton	$RU = \exp(-kt)$	(6)
Page	$RU = \exp(-kt^n)$	(7)
Modified Page	$RU = \exp(-kt^2) + bt$	(8)
Thompson	$RU = \exp\{[-a - (a^2 + 4bt)^{1/2}]/2b\}$	(9)

t = drying time (min); *k* = drying constant (min); *a*, *b*, *c*, and *n* = model coefficients (dimensionless); RU = moisture content ratio. RU was determined according to equation: $RU = (Ut - Ue)/(Uo - Ue)$, where *Ut* is the moisture content at time t ($kg_a\ kg_{ms}^{-1}$), *Uo* is the initial moisture content ($kg_a\ kg_{ms}^{-1}$), and *Ue* is the moisture content at equilibrium ($kg_a\ kg_{ms}^{-1}$).

The experimental data of the drying process were evaluated using regression analysis, and model selection was conducted based on the coefficient of determination (R^2) of the mean relative error (P) and estimated mean error (SE) using the Statistical Analysis System software. The experimental design used was completely randomized and had four replications. P and SE values were calculated according to Equations 10 and 11:

$$P = \frac{100}{n}\sum_{i=1}^{n}\frac{\left|Y_i - \hat{Y}_i\right|}{Y_i} \tag{10}$$

$$P = \frac{100}{n}\sum_{i=1}^{n}\frac{\left|Y_i - \hat{Y}_i\right|}{Y_i} \tag{11}$$

Where:
Y_i = observed value,
$\hat{Y}_i$ = estimated value,
n = number of observed data,
GLR = residual degrees of freedom (number of observed data − the number of parameters of the model).

RESULTS AND DISCUSSION

Figure 1 shows the drying curves for macaúba almonds at temperatures of 40 °C, 50 °C, and 60 °C. When the almonds were dried at 40 °C, the time required to reduce the moisture content to approximately 0.02 $kg_a\ kg/_{ms}^{-1}$ was 404.4 h. At 50 ° C, that time was 169.08 h, and at 60 °C, the required drying time was 34.08 h, i.e., 11.86 times shorter than that at a temperature of 40 °C. The value of 0.02 $kg_a\ kg_{ms}^{-1}$ was used as a parameter because it corresponded to the hygroscopic equilibrium.

The drying time decreases with an increase in the temperature; in addition, the inclination of the curves increases because the heat transferred from the air to the almond is greater, thereby resulting in a faster removal of water at higher temperatures (BAPTESTINI et al., 2015). The increase in the temperature of the drying air results in a higher rate of water removal from the product. This is due to a higher water vapor pressure between the almond and the air (SMANIOTTO et al., 2017). Another possible reason of a shorter drying time at a temperature of 60°C is the fact that the level of molecular vibration of water molecules increases with a rise in temperature, thereby contributing to a faster diffusion of water (SILVA et al., 2020). Borompichaichartkul et al. (2009), studied the quality of macadamia (*Macadamia integrifolia*) after they were subjected to drying treatments at temperatures of 50 °C, 60 °C, and 70 °C; they also found that the increase in drying temperature resulted in a higher drying rate of macadamia nuts.

The drying kinetics of macaúba almonds are controlled by the characteristics of the almonds as well as variables such as temperature, velocity, and relative humidity of air.

However, in Figure 1, it is evident that drying occurred in two stages under all treatment conditions (40 °C, 50 °C, and 60 °C). In the first stage, there was a rapid reduction in the moisture content of the almonds; in the second stage, although slower than that in the first stage, the reduction in moisture content continued. This two-stage drying behavior was also described by Silva et al. (2017), in their study of macaúba fruit drying and its influence on oil quality.

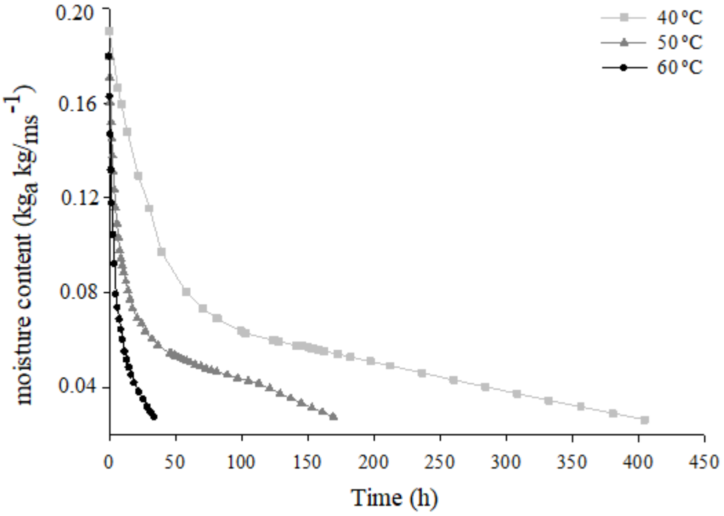

Figure 1. Dispersion of moisture content according to the drying time of macaúba almonds at temperatures of 40 °C, 50 °C, and 60°C.

The drying process under all treatment conditions (40 °C, 50 °C, and 60°C) occurred predominantly during the drying period at a decreasing rate. This process occurs due to the presence of a greater resistance to water transfer inside the almond, resulting in a higher evaporation rate at the surface than that inside the almond (KASHANINEJAD et al., 2007). A predominant physical mechanism is suggested to underlie the drying process, i.e., the occurrence of moisture diffusion. According to Brooker, Bakker-Arkema, and Hall (1992), heat transfer in the diffusion process is not compensated by mass transfer because moisture transport has a higher internal resistance; thus, the temperature of the product can equal the temperature used during the drying process.

Figure 2 shows the values of moisture content ratio for temperatures of 40 °C, 50 °C, and 60 °C. It represents the loss of water from macaúba almonds as a function of time for the decreasing drying period.

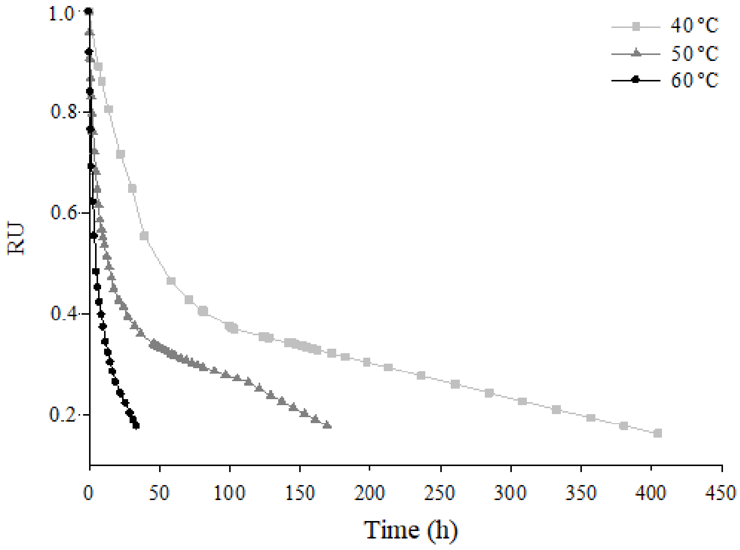

Figure 2. Dispersion of moisture content ratio (RU) of macaúba almonds expose d to temperatures of 40 °C, 50 °C, and 60 °C.

The curves were fitted by nine different mathematical models presented in the literature to describe the drying process, and the results are shown in Table 2 According to Table 2, with the exception of the Newton and Henderson and Pabis models at temperatures of 40 °C and 50 °C, all mathematical models that fitted the experimental drying data had R^2 of > 0.95. Silva et al. (2017), studied the drying process of macaúba fruits and its effect on oil quality and found that the models, approximation of diffusion, Henderson and Pabis, logarithmic, Midilli, Newton, Page and Modified Page, had R^2 values > 0.99 for the experimental values of drying.

Table 2. Estimates of model parameters applied for the representation of the experimental data and their respective coefficients of determination (R^2), mean relative error (P), and estimated mean error (SE).

Models	T (°C)	Parameters (1)					R^2	P	SE
		k	*C*	*A*	*N*	*b*			
Approximation of diffusion	40	5.5127 10^{-4}	-	0.5384	-	7.0026 10^{-2}	0.9986	2.6768	0.0111
	50	2.80454 10^{-3}	-	0.5491	-	3.1652 10^{-2}	0.9979	2.6765	0.0150
	60	5.9369 10^{-3}	-	0.5180	-	8.5329 10^{-2}	0.9996	1.2360	0.0067
Henderson and Pabis	40	9.7390 10^{-5}	-	0.8147	-	-	0.9311	17.584	0.0751
	50	2.2848 10^{-4}	-	0.7452	-	-	0.8944	21.875	0.1030
	60	1.1401 10^{-3}	-	0.8411	-	-	0.9525	18.220	0.0770
Logarithmic	40	2.7500 10^{-4}	0.2462	0.7023	-	-	0.9854	9.5584	0.0355
	50	1.3695 10^{-3}	0.2824	0.6432	-	-	0.9844	10.124	0.0409
	60	2.9707 10^{-3}	0.2231	0.7330	-	-	0.9932	7.1812	0.0301
Midilli	40	5.4330 10^{-3}	-	1.0385	0.6014	4.3039 10^{-6}	0.9913	6.4241	0.0279
	50	3.6009 10^{-2}	-	1.0585	0,4467	1.0881 10^{-5}	0.9942	5.5899	0.0251
	60	0.0163	-	1.0259	0,6588	5.4420 10^{-5}	0.9973	3.8050	0.0195
Modified Midilli	40	3.7516 10^{-3}	-	-	0,6399	4.6849 10^{-6}	0.9991	28.020	0.0122
	50	0.0238	-	-	0,4948	1.2581 10^{-5}	0.9931	6.1226	0.0270
	60	0.0131	-	-	0,6902	5.8259 10^{-5}	0.9970	3.9813	0.0196
Newton	40	1.2948 10^{-4}	-	-	-	-	0.8754	25.6310	0.0981
	50	4.1971 10^{-4}	-	-	-	-	0.7144	39.5499	0.1595
	60	1.5199 10^{-3}	-	-	-	-	0.9119	28.6272	0.1037
Page	40	7.9211 10^{-3}	-	-	0,5413	-	0.9864	6.6634	0.0338
	50	0.0375	-	-	0,4181	-	0.9883	6.7889	0.0350
	60	0.0230	-	-	0,5786	-	0.9933	5.6319	0.0291
Modified Page	40	1.3139 10^{-4}	-	-	0,5413	-	0.9864	6.6634	0.0338
	50	3.8908 10^{-4}	-	-	0,4181	-	0.9883	6.7889	0.0350
	60	1.4760 10^{-3}	-	-	0,5786	-	0.9970	5.6319	0.0291
Thompson	40	-	-	-3.9195	-	5.4490 10^{-2}	0.9892	6.6446	0.0301
	50	-	-	0.6941	-	7.2092 10^{-2}	0.9806	10.6454	0.0452
	60	-	-	2.5344	-	0.1260	0.9962	4.8008	0.0220

(1) Determination for each temperature was performed in four replicates.

In order to represent the drying process of agricultural products, a combined analysis of the three statistical parameters (R^2, P, and SE) is necessary (CORRÊA et al., 2010; BAPTESTINI et al., 2015). On analyzing Table 2, it was found that among the nine mathematical models used to predict the macaúba almond drying process, only the models approximation of diffusion, Midilli, Page, and Modified Page presented a P of <10%. According to Mohapatra and Rao (2005), models that present P values of >10% are considered inadequate for the description of a given process. P indicates the deviation of the observed values in relation to the curve estimated by the model (KASHANINEJAD et al., 2007). Thus, the lower the P value, the lower the deviations between the experimental values and those estimated by the model (SIQUEIRA; RESENDE; CHAVES, 2013).

SE values were also calculated in addition to R^2 and P values. This parameter indicates the ability of a specific model to describe a physical process, and the lower its magnitude, the better the quality of the model's fit in relation to the observed data (BAPTESTINI et al., 2015). Thus, the joint analysis of the three statistical parameters showed that only the approximation of diffusion, Midilli, Page, and Modified Page models were able to describe the drying process of macaúba almonds at all drying air conditions. Smaniotto et al. (2017), studied the drying kinetics of sunflower seeds and also found that the Midilli, Page, and approximation of diffusion models exhibited the best fits for the experimental data of sunflower drying. Dhanushkodi, Wilson, and Sudhakar (2017), studied the mathematical modeling of the drying process of cashew nuts in a solar biomass hybrid dryer and observed that the Page model was the best model for describing the process of cashew nut drying.

CONCLUSION

The increase in drying temperature caused a reduction in the drying time. In addition, the curves' inclination increased because the heat transferred from the air to the almonds was higher, which resulted in a faster removal of water at higher temperatures.

According to the joint analysis of the three statistical parameters (R^2, P, and SE), the approximation of diffusion, Midilli, Page, and Modified Page models were found to be the models that best describe the process of macaúba almonds with the aim of subsidizing the design of industrial dryers.

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